Future Kaon Physics at Fermilab

How we're **Still** going to measure $K^+ \rightarrow \pi^+ \nu \bar{\nu}$

Peter S. Cooper, Fermilab

May 13, 2004

I. Recent history.

II. Physics goals and situation.

III. A new technique and its challenges

IV. Our immediate plans

V. Future Kaon Physics at Fermilab

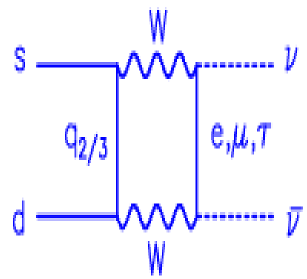
CKM Status and how to proceed

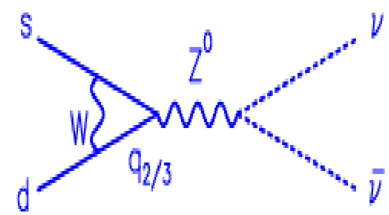
- CKM(E921) at Fermilab is an approved experiment to measure Br[$K+\rightarrow \pi+ \nu$ n] with 100 signal / <10 background in a high flux separated kaon beam at 22 GeV/c
- **P5** stops **CKM** - Oct 2003

  P5 judged *CKM to be an elegant world class experiment* which *based on present budgetary models should not proceed.*
- Adapt to an unseparated ~45 GeV/c beam in KTeV hall - **P940**
  - Demonstration of μMegas in NA48 ® tracking in 230MHz tractable
  - Other 3 trackers unchanged (2 RICHes + Straws in vacuum)
  - Vetoing photons gets easier (E_{π^0} > 1 GeV ® >7 GeV)
  - Accidental backgrounds?

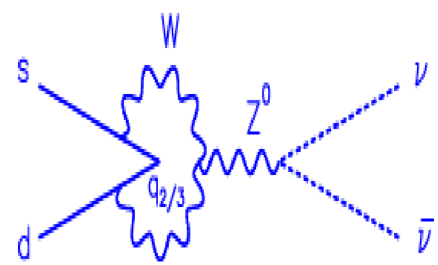
Primary Physics Goal: Precision Measurement of Br[$K^+ \rightarrow \pi^+ \nu \bar{\nu}$]

This decay is determined by loop processes to high order in the SM, and hence has a reach for *new physics at the EW scale and beyond*.





The SM rate can be reliably calculated; hence any deviation in the measured rate is a signal for new physics.



Measuring $|V_{td}|$ with $K^+ \rightarrow \pi^+ \nu \bar{\nu}$

u c t | C K M | d s b

- $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ is the best way to measure $|V_{td}|$ in the Standard Model
  - Structure of K^+ controlled by measurement, NO final state interactions.
  - Theoretical uncertainties are small (m_{charm}) and robustly estimated. (~8%)
  - Need 100 signal events with <10 background (6%) to match theory error.
- Experimental Challenge
  - $Br[K^+ \rightarrow \pi^+ \nu \bar{\nu}] = (8 \pm 1) \times 10^{-11}$ (Standard Model)
  - 3 clean events seen in BNL787 /949 ($Br = 15^{+13}_{-9} \times 10^{-11}$)
- The tyranny of tiny decay rates
  - 100 events / 10^{-10} (Br) / 1% (acc) = 10^{14} K decays must be studied
  - 10^7 sec/year $\rightarrow$ 10^7 K decay /sec to see 100 in 1 year
  - Need to control background to 10^{-11} of all K^+ decays

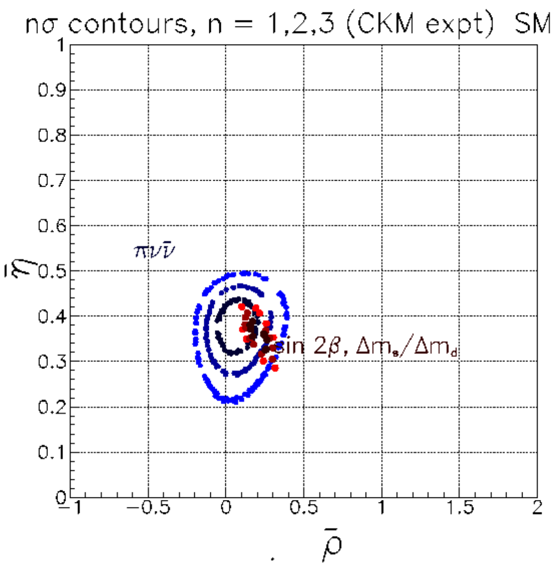
Challenging the Standard Model of CP Violation

Consider the Quartet of "Golden Mode" measurements:

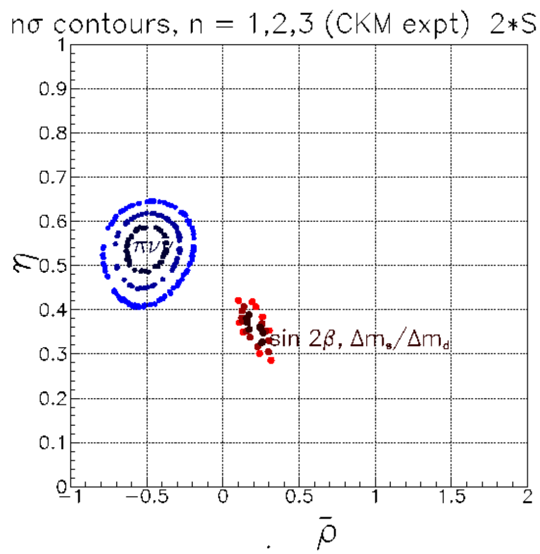
$\sin(2\beta)$, $K^0 \to \pi^0 \nu\bar{\nu}$, $K^+ \to \pi^+ \nu\bar{\nu}$,

$\Delta m_d / \Delta m_s$ in B_d^0 and B_s^0 Decays

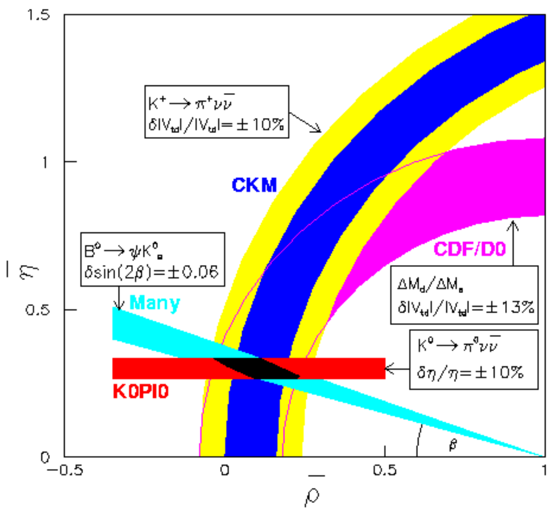
$\Gamma(\pi\nu\nu)$ = SM



$\Gamma(\pi\nu\nu)$ = 2xSM

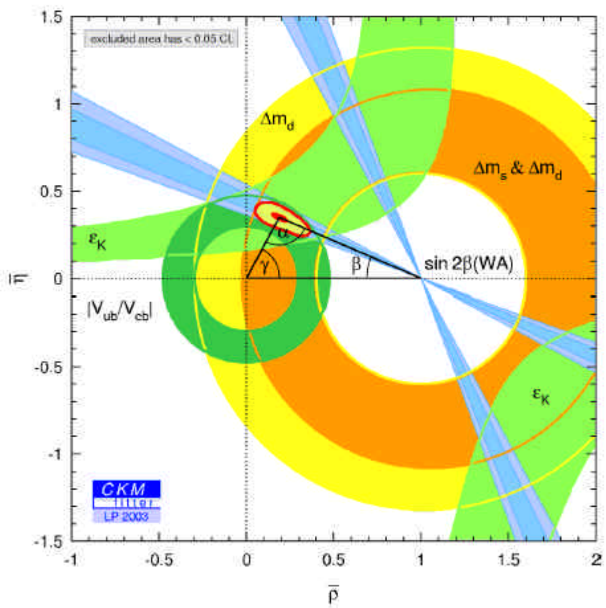


expected sensitivities



CKM Fitter Results, D. Jaffe (BNL).

Hasn't B physics done it all already?



Who will measure orthogonal to sin 2β?

Bs/Bd mixing CDF /D0 / BTeV /LHCb

But $\xi(\Delta m_s/\Delta m_d) = 1.15 \pm 0.05^{+0.12}_{-0.00}$

? 1.25 ± 0.10

B_s ? D_sK BTeV / LHCb

$K^+ \to \pi^+ \nu \bar{\nu}$ P940

•hep-ph/0312259

$B \to \pi\pi$, New Physics in $B \to \pi K$ and Implications for Rare K and B Decays

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Abstract

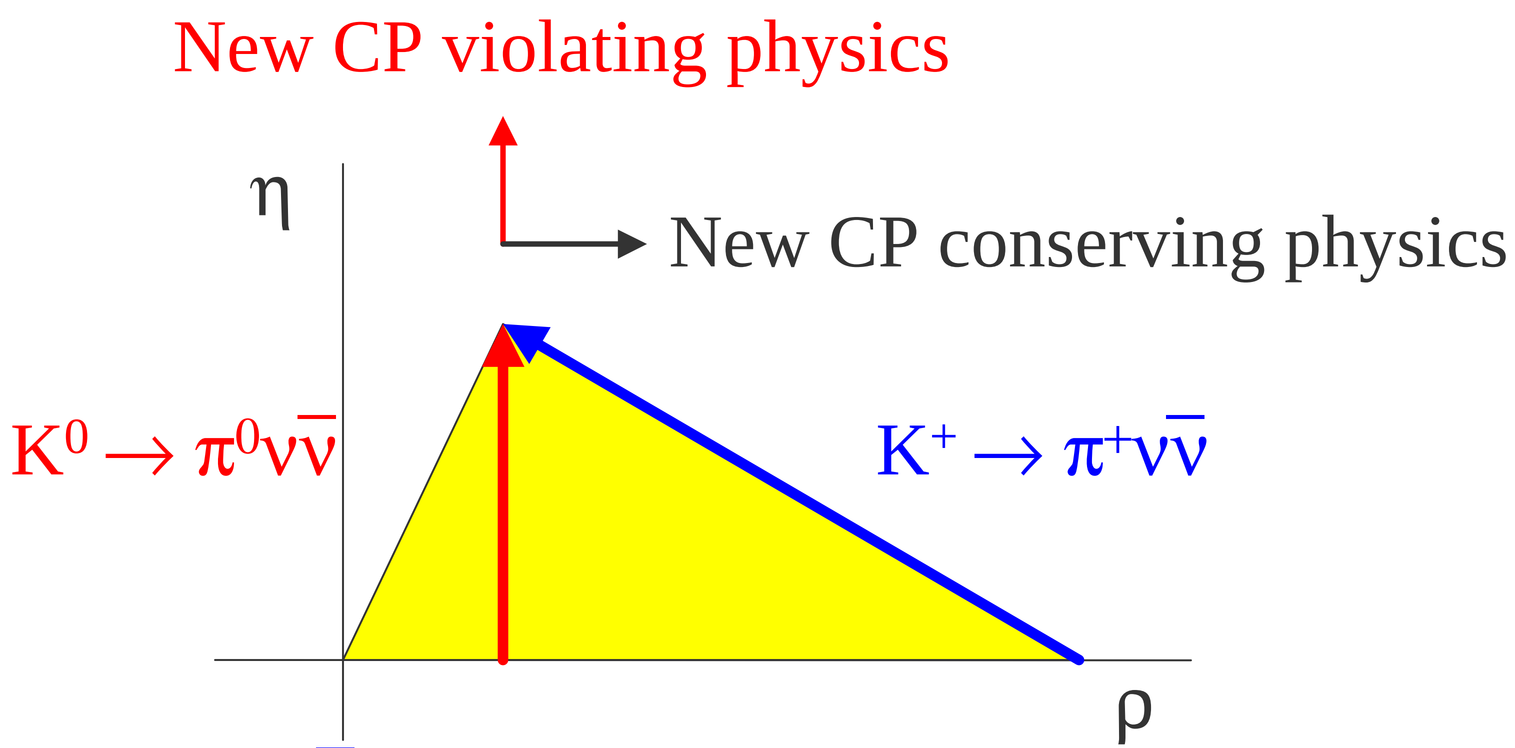
The measured $B \to \pi\pi, \pi K$ branching ratios exhibit puzzling patterns. We point out that the $B \to \pi\pi$ hierarchy can be nicely accommodated in the Standard Model (SM) through non-factorizable hadronic interference effects, whereas the $B \to \pi K$ system may indicate new physics (NP) in the electroweak (EW) penguin sector. Using the $B \to \pi\pi$ data and the $SU(3)$ flavour symmetry, we may fix the hadronic $B \to \pi K$ parameters, which allows us to show that any currently observed feature of the $B \to \pi K$ system can be easily explained through enhanced EW penguins with a large CP-violating NP phase. Restricting ourselves to a specific scenario, where NP enters only through Z^0 penguins, we derive links to rare K and B decays, where an enhancement of the $K_L \to \pi^0 \nu\bar{\nu}$ rate by one order of magnitude, with $BR(K_L \to \pi^0\nu\bar{\nu}) > BR(K^+ \to \pi^+\nu\bar{\nu})$, $BR(K_L \to \pi^0 e^+ e^-) = O(10^{-10})$, $(\sin 2\beta)_{\pi\nu\bar{\nu}} < 0$, and a large forward-backward CP asymmetry in $B_d \to K^* \mu^+\mu^-$, are the most spectacular effects. We address also other rare K and B decays, ε'/ε and $B_d \to \phi K_S$.

•hep-ph/0311353 *Lepton flavor mixing and K® pn`n decays*, Y. Grossman, G. Isidori, H. Murayama

•hep-ph/0112135 *K⁺® p⁺n`n a rising star on the stage of flavor physics*, G. D'Ambrosio, G. Isidori

•many more

New Physics sensitivity in $K^+ \to \pi^+ \nu \bar{\nu}$



$K^+ \to \pi^+ \nu \bar{\nu}$ Sensitive to all new physics in $s \to d$ transitions

$K^0 \to \pi^0 \nu \bar{\nu}$ Sensitive to only CP violating $s \to d$ new physics

Other Physics Measurements

- π^+ decay physics
  - $\Gamma[\pi^+\to e^+\nu(\gamma)]/\ \Gamma[\pi^+\to\mu^+\nu(\gamma)]$ is calculated to 0.05% in the SM
  - Helicity suppresses the dominant V-A and IB amplitudes
  - $\pi^+\to e^+\nu\gamma$ Dalitz plot – access to non V-A terms in hadronic weak current
  - An excellent place to search for models like leptoquarks, multiple Higg, etc.
- Other K^+ decay physics
  - All the other K decays studies from the CKM proposal remain
    - K_{e3}, K_{e4}, $K_{\mu 3}$, $K_{\mu 4}$, $K^+\to\pi^+e^+e^-$, $K^+\to\pi^+\mu^+\mu^-$
    - Lepton flavor violation - $K^+\to\pi^-\mu^+\mu^+$, etc.
    - T odd correlations in $K^+\to\pi^+l^+\nu\gamma$
  - $\Gamma[K^+\to e^+\nu(\gamma)]/\ \Gamma[K^+\to\mu^+\nu(\gamma)]$, $K^+\to e^+\nu\gamma$ in parallel with pion decays

Changes in the physics situation

What's changed since the CKM approval in 2001?

- Another $K^+ \to \pi^+ \nu \bar{\nu}$ event from BNL E949.
- B_s mixing isn't going to be measured at the SM level (17 ps^{-1}) soon.
- Some unusual CP violation results are emerging at Belle
  - e.g. $B^0 \to \phi K_S^0$ asymmetries disagrees with ψK_S^0 (& $K^+K^-K_S^0$, $\eta' K_S^0$)
- Lack of 1st row unitarity (~2.5σ) and new measurements of V_{us} topical
- There is experimental evidence for non V-A terms in the pion hadronic weak current in $\pi^+ \to e^+\nu\gamma$
  - 5σ claim by PiBeta for tensor form-factor F_T/F_V= -0.061±0.011

    hep-ex/0311013, hep-ex/0312029
  - ISTRA at IHEP also reported a non-zero tensor form-factor.

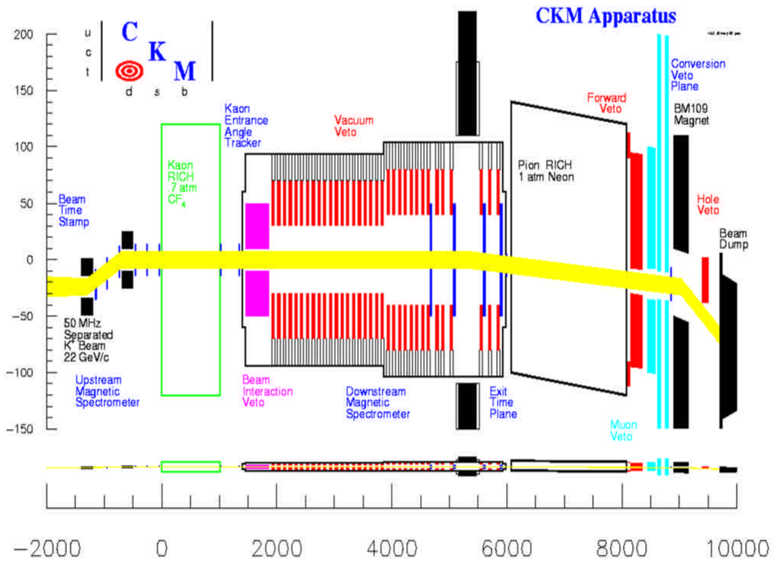
    Phys.Lett.**B243** (1990)308, hep-ph/0307166

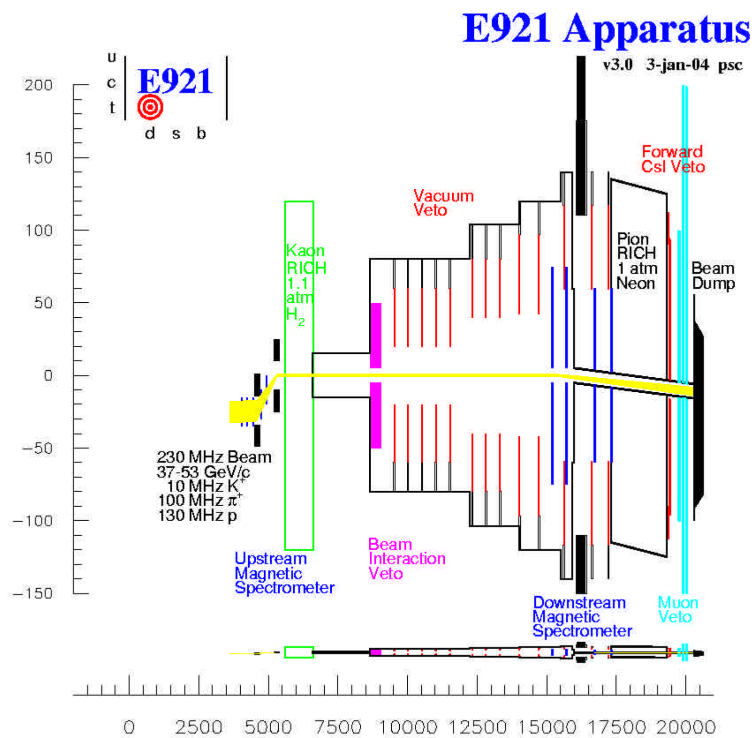
Experimental Technique

- High Flux Un-separated 37-53 GeV/c Beam - 4% K^+
  - Proton / π^+ : 120 / 100, 230 MHz total, 1x1 cm^2, 0.1x0.1 $mRad^2$
  - 10 MHz K^+, 1.7 MHz decay in the acceptance.
  - 5 $\times 10^{12}$ 120 GeV proton /sec in slow spill from the Main Injector to produce the required K^+ beam (17% of design intensity)
  - Debunched proton beam required (~10% 53MHz ripple ok).
- Apparatus
  - Decay in flight spectrometer with both velocity (RICH) and momentum (magnetic) spectrometer both both K^+ and π^+.
  - Significant requirements on photon vetoes
  - All detector technologies used are well established
  - **Redundancy** is critical to measure all backgrounds
  - Exploit signal regions on both sides of $K^+ \to \pi^+\pi^0$.

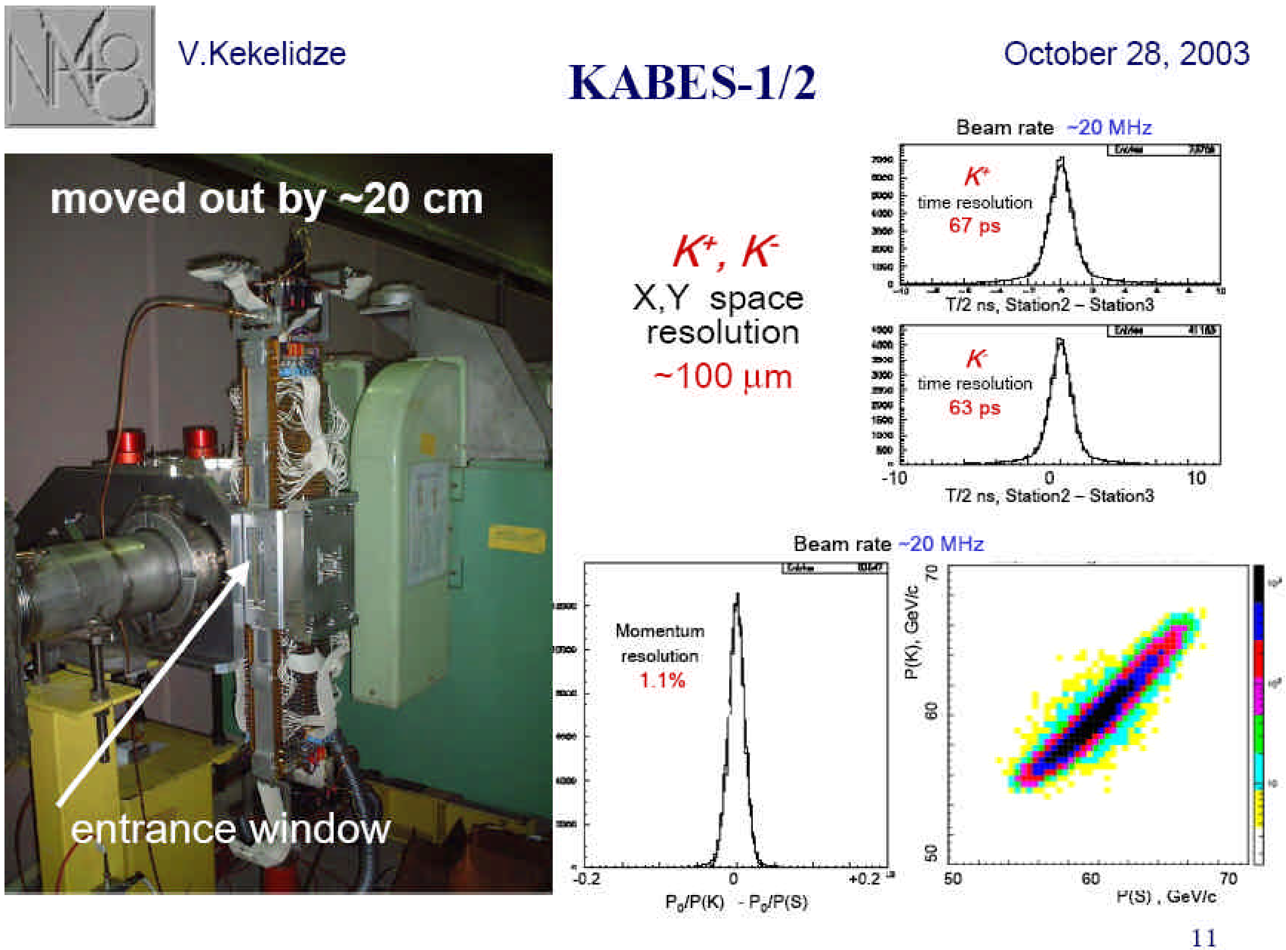
Apparatus

- Decay in flight
- Redundant high rate detectors and veto systems.
- separated K+ beam at 22 GeV/c. Un-separated + beam at 37-53 GeV





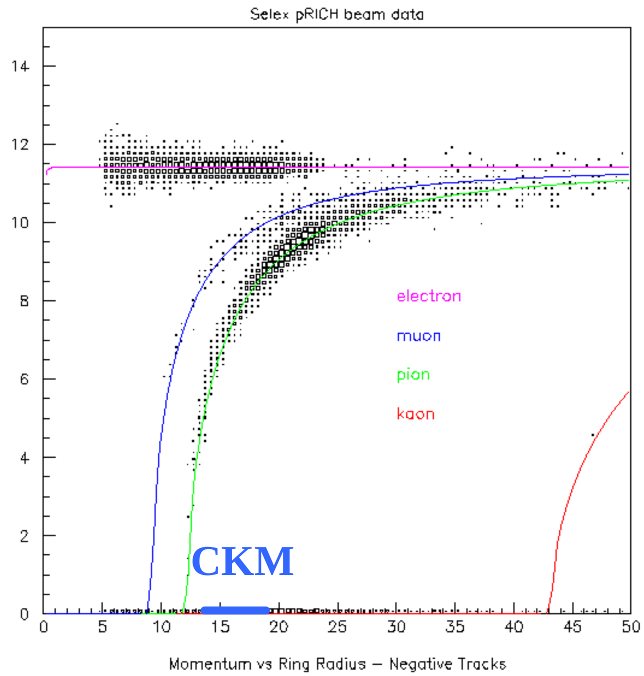
NA48 KABES data

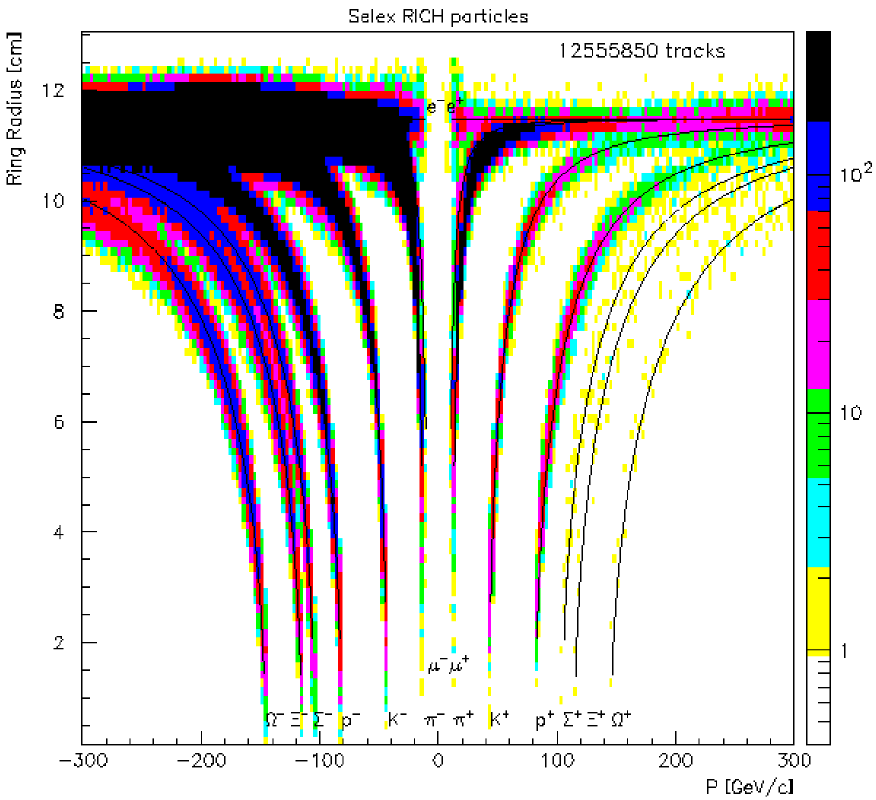


Ring Imaging Cherenkov Counters

u c t C K M d s b

- High rate high resolution
- Matched to momentum resolution
- Based on successful Selex RICH
- Photo-detectors are individual PMTs

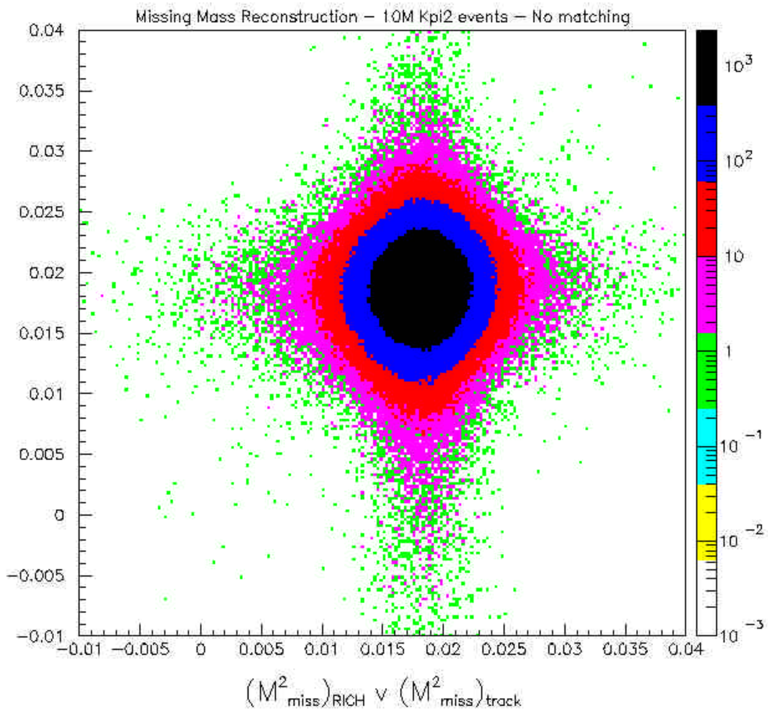




Simulated Spectrometer Performance

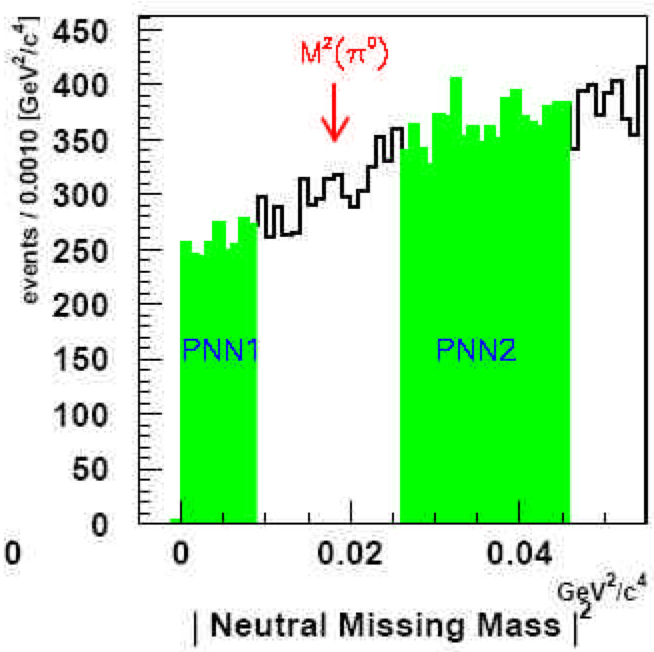
- Missing mass resolution for $M^2_{\pi^0}$ from $K^+ \rightarrow \pi^+ \pi^0$
- Matched resolution from momentum and velocity spectrometers
- Low non-Gaussian tails
- Uncorrelated measurements

  Backgrounds from Mis-measurements to be studied and quantified from the data
- Study needs to be redone for P940



Acceptance

- Acceptance was re-evaluated. Decay fraction increased 13% $\rightarrow$ 16.5%
- PNN2 acceptance limited to 1.4x PNN1 pending more serious background studies
- Nearly identical sensitivity as CKM for same 120 GeV beam incident.



parameter	CKM	E921
$K^+ flux[MHz]$	30	10
beam-sec/year	0.75×10^7	0.75×10^7
years of data	2	2
sensitive K decays	5.8×10^{13}	2.5×10^{13}
nominal Branching ratio	1×10^{-10}	1×10^{-10}
taxes (other losses)	-15%	-15%
PNN1 (s+b)	$95+ \leq 10$	$44+ \leq 4$
PNN2	$(130+ \leq 40)$	$62+ \leq 20$
total	$95+ \leq 10$	$106+ \leq 24$
Br precision	$< 11\%$	$< 12\%$

Backgrounds Remaining

Background Source	Effective BR ($\times 10^{-12}$) CKM	P940
$K^+ \to \mu^+ \nu_\mu$	< 0.04	-
$K^+ \to \pi^+ \pi^0$	3.7	~5
$K^+ \to \mu^+ \nu_\mu \gamma$	< 0.09	-
$K^+ A \to X K^0_L \to \pi^+ e^- \nu$	< 0.14	TBD
$K^+ A \to \pi^+ X$ (trackers)	< 4.0	TBD
$K^+ A \to \pi^+ X$ (gas)	< 2.1	TBD
Accidentals (K^+ + beam track)	-	TBD
Accidentals (2 K^+)	0.51	0.17
TOTAL	<10.6	TBD

Our plan

- We are in the middle of this redesign now – we need to:
  - Complete the unseparated beamline design for NM2
  - Assess KABES feasibility in a 230 MHz beam
  - Re-evaluate backgrounds from Kaon interaction in detectors
  - Estimate backgrounds from non-kaon interaction accidentals
  - Evaluate PNN2 cuts, acceptance and backgrounds
  - Re-assess losses from deadtime, reconstruction, …
- Our Plan
  - Complete the list above
  - Have external technical review of the redesign (a-la CKM)
  - Return to Fermilab and the PAC with a vetted re-design
  - Time scale of months

Future Kaon Physics at Fermilab

- Fermilab is planning a Proton Driver to increase fluxes by ~10x
  - Both an 8 GeV SCRF proton Linac and an 8/16 GeV high flux conventional synchrotron are under consideration.
  - Physics goals include sensitivity neutrino experiments, …
  - Time frame is the next decade (~2015)
- High Sensitivity Kaon physics is a natural for this machine - **but**
  - The Main Injector was sold on the same promise in ~1989
  - Save the KTeV 1999 run no kaon physics will be done in the first decade of main-injector operation
- If Fermilab and US-HEP aren't interested in a kaon physics program for today discussing one in a decade is fatuous.

Extra Slides

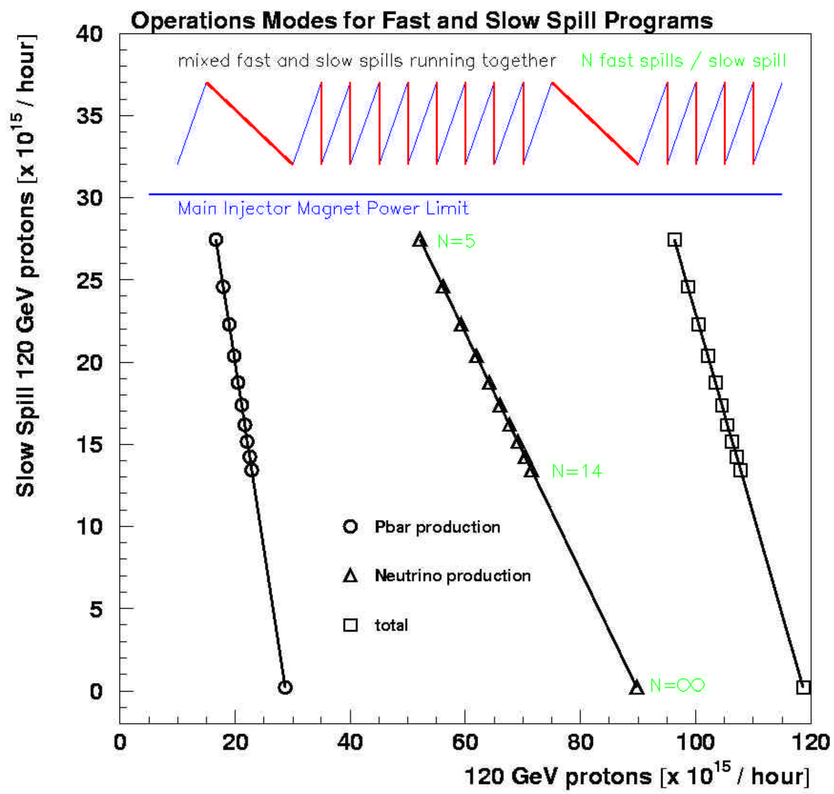
Proton Economics

o We require debunched protons from the Main Injector (10% 53MHz ripple is OK).

o Separate fast (neutrino+Pbar) and slow spill Main Injector cycles make these different modes of operation independent by timesharing

o N=8 fast cycles / slow cycle gives both fast and slow spill 2/3 of the maximum available to either.

o Setting N in this model is a program planning decision.



P5

- The Particle Physics Project Prioritization Panel (P5) reviewed BTeV, CKM and the Tevatron detector upgrades; concluding for CKM:

Evaluation – The subpanel was impressed with the excellent work of the proponents on the design of the experiment and their successful prototyping results. CKM is an elegant world-class experiment, which would be able to produce important physics results. However, the committee assigns it a lower priority than the BTeV experiment. The main reason is that BTeV has a much broader physics program at a comparable cost.

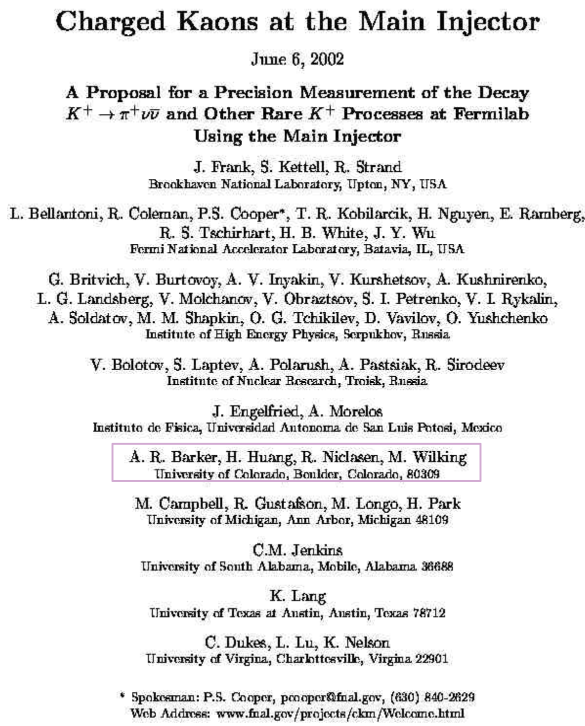
Suggestions Based on Prioritization – The present Fermilab plan calls for a similar funding profile and time-line for BTeV and CKM construction, with both starting to take data around 2009. The P5 Subpanel believes that this plan is likely to be too ambitious given the need to optimize the physics from the Tevatron Collider, as well as the desire to have BTeV completed promptly. *Based on current budgetary models, P5 does not recommend proceeding with CKM.*

Changes to the apparatus

- Beamline — existing NM2 beamline and NM3-4 detector hall (KTeV)
  - 120 GeV proton transport estimated at 250K\$+50% (C. Brown)
  - Target station can be modified – designed for required intensity
- Kaon RICH — 10 $\rightarrow$ 12m, radiator gas to H_2 at 1.1 atm – only sees beam Kaons
- DMS — same strawtube in vacuum design as CKM, hole for 10cm beampipe
- Pion RICH
  - Same basic design as CKM (1atm Ne, 3000 1/2in PMTs)
  - Optics modified to accommodate beampipe down the middle.
- Photon Vetoes
  - 90% of photons now hit CsI $1-\varepsilon \sim 3\times10^{-6}$ for E>1 GeV
  - VVS - 5 existing Pb-scint rings from KTeV + 9 new ones of CKM design
  - Photon energy threshold can be >1.5 MIP everywhere.
- Muon Vetoes — combined KTeV MVS + descoped CKM design
- UMS — replace CKM MWPC's with μMegas of KABES design

P940 Collaboration

- Groups from 4 national laboratories and 5 universities.
- 44 people including 6 postdocs + students
- Roots in KTeV, Selex, HyperCP, CDF, BNL787/E949, BNL871, IHEP-Istra, -Lepton, -Sphinx
- Substantial experience in rare and ultra rare kaon decay experiments
- Collaboration will double with time. The technical review should help with this.



Charged Kaons at the Main Injector

June 6, 2002

A Proposal for a Precision Measurement of the Decay $K^+ \to \pi^+ \nu\bar{\nu}$ and Other Rare K^+ Processes at Fermilab Using the Main Injector

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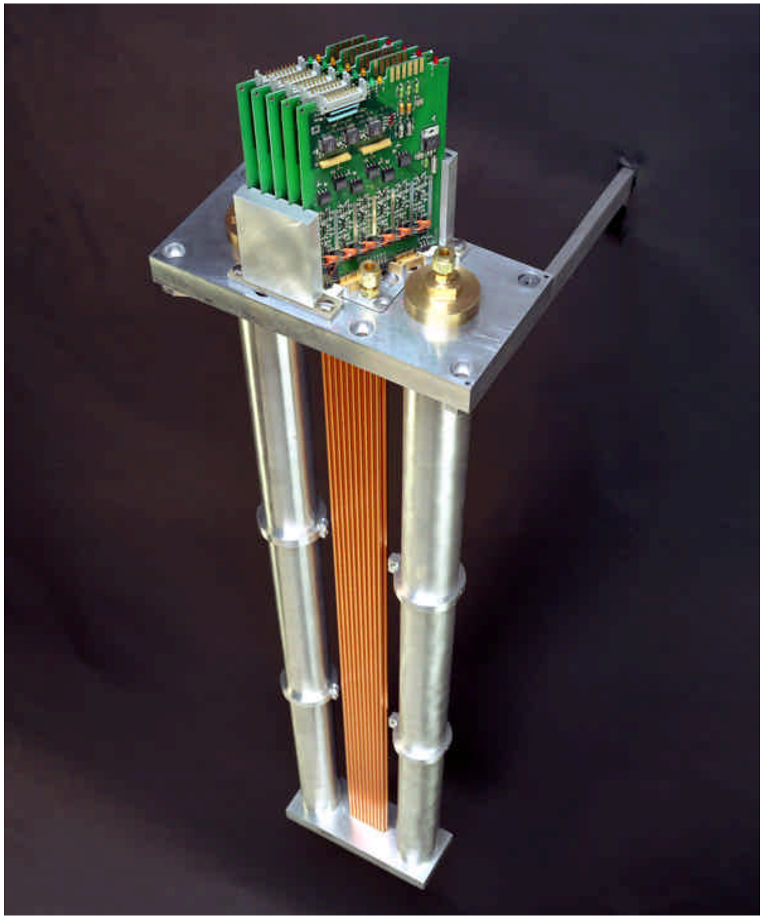
What do we need

- A reaffirmation that Fermilab is still committed to the world class P940 physics program.
- Near term support from Fermilab to complete the redesign and review.
  - Fermilab technical support
    - main need is for beam-line design and cost
    - engineering design
    - cost estimation
  - Support for Russian visitors
  - Travel support to interact with NA48
  - Support for the technical review committee
- The collaboration, particularly the university groups, need support and encouragement in order to persevere.

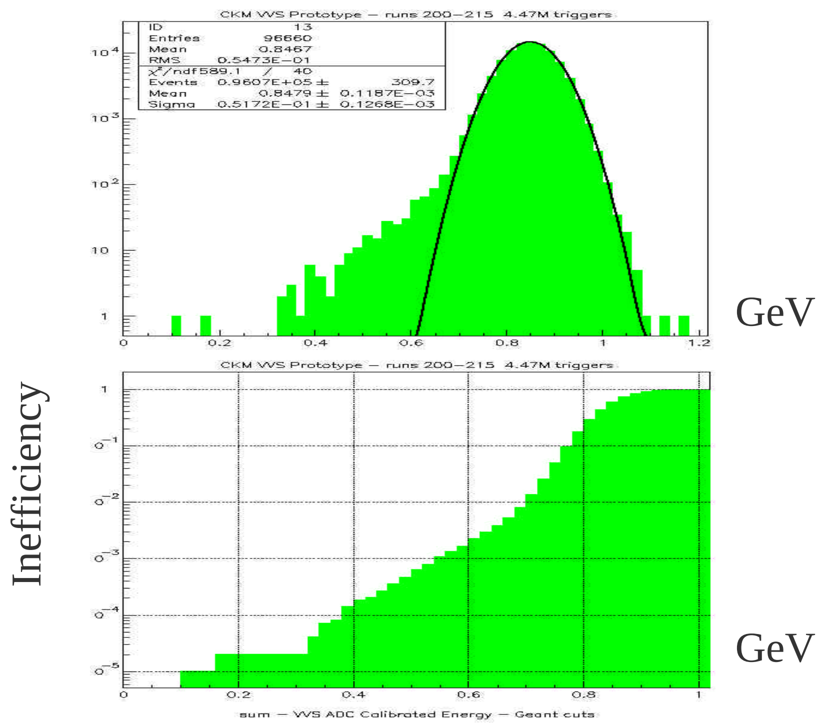
Straws in Vacuum: Old Wine, New Bottle.

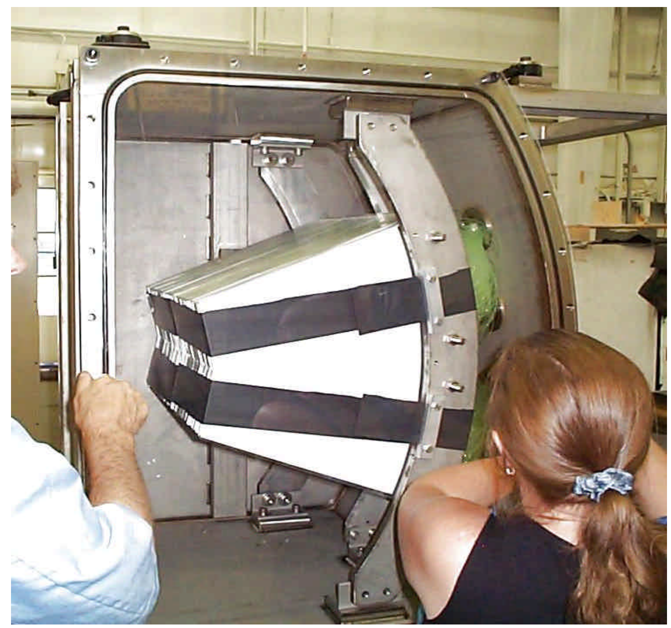
- Mechanical properties extensively studied. (Fermi-Pub 02-241-E)
- Prototype operating in vacuum.
- Proven Principle. Now ready for detailed engineering.



Photon Veto Inefficiency and Technology

- 0.3% VVS Prototype built
- Tested at JLAB in an e⁻ beam
- Achieved $<1\times10^{-5}$ (3×10^{-6}) veto inefficiency at 1 GeV (required 3×10^{-5})





KABES μMEGAS from NA48